White Paper for Frontiers of Plasma Science Panel

Date of Submission: 06/19/2015

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Title: Academic and National Laboratory Collaborations to study the properties of Warm Dense Matter.

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(Limit text to 3-pages including this form. Font Times Roman size 11. 1 page of references and 1 page of figures may also be included. Submit in PDF format.)

• Describe the research frontier and importance of the scientific challenge.

Warm dense matter (WDM) is an extreme material state that lies between condensed matter and high temperature plasma, and is found in the interior of large gas and ice giant planets $^1$ $^2$, as well as on the pathway to inertial confinement fusion (ICF) $^3$. WDM occurs at a “malfunction junction” of knowledge, where the limiting approximations applied for understanding matter break down. This makes it complex and exciting: exciting, because WDM tests the limits of scientific understanding of the phenomena by which atoms, ions and electrons interact and organize over a range of extreme conditions; and complex, because the response of WDM cannot be predicted by a single conventional scientific approach. It is also the complexity of WDM that spurs the imagination. For example, metallic hydrogen, a warm dense state of hydrogen, is continually sought after in experiments more than 80 years after it was first predicted. Diamond rain in the dense methane atmosphere of Neptune and superionic water on Uranus are spectacular predictions of materials in warm dense states. The limits of WDM are not sharply defined but
typical definitions include a region of phase space around 1eV and 1g/cc where the boundaries of different material regimes cross. Figure 1 is a representative temperature density plot for an ICF ignition capsule at 10keV and densities of 1kg/cc as well as the states of naturally occurring planetary systems. The pathway to ICF goes through WDM. Understanding materials in these warm dense states has been specifically outlined as a priority in ICF science in “Report of the Interagency Task Force on High-Energy-Density physics” and “Frontiers in High-Energy-Density Physics: The X Games of Contemporary Science” in two thrust areas: material properties and compression dynamics.

The United States has made investments into large high energy density physics facilities for WDM research, but currently there are no U.S. academic programs with a focus on experimental research in this field. Hence, there is a strong need to establish a vibrant U.S. academic research program in WDM to train the next generation of WDM scientists. This white paper focuses on the support for educating and research work of a graduate student through funded collaborations between academic institutions and national laboratories to help establish academic Warm Dense Matter research in the U.S.

- **Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.**

WDM requires high temperatures and pressures that are difficult to produce and interrogate in the laboratory. Techniques such as isochoric heating with ions or x-rays have been used to produce WDM, but the majority of WDM research uses shockwave compression. A shockwave is generated when a pressure impulse is applied to a sample creating a propagating discontinuity in thermodynamic properties. In these experiments the WDM state is inertial confined by the finite time it takes for the shockwave to traverse the sample. The material properties and the applied pressure amplitude determine the compression and heating in the sample. The ultimate limit for these experiments is the energy density that can be imparted onto the sample, in laser and pulse power experiments billions of atmospheres of pressure can be imparted onto a sample achieving the highest pressures on earth.

The thermodynamic properties of WDM are studied by the connection between density, pressure and internal energy referred to as the equation of state (EOS). These thermodynamic properties are measured across a shock by a range of different techniques provide a stringent set of conditions, which must be met to test the predictions of WDM models. The models are typically on the atomic level using a range of theoretical constructs like density functional theory or quantum molecular dynamics. From these simulations thermodynamic properties are inferred. Statistical mechanics is the link between the microscopic assembly of states and the continuum properties like pressure and temperature. While EOS measurements do directly aid in understanding the ICF compression process and planetary interiors, the link to microscopic phenomena is important. It is important because the models can be used to infer properties and physical processes that cannot be measured. The use of reverberating shockwaves in a sample sandwiched between two windows will achieve high compression and pressure. This approach will generate the WDM state and will allow us to select a range of pressure density states by judicious choice of the applied pressure and window materials.

Facilities, like the Nike laser at the Naval Research Laboratory (NRL), offer the capability to generate WDM states using two-kilojoules of laser energy and the ability to probe the material with diagnostics such as free surface velocity measurements, and time resolve x-ray radiography. Using time resolved
x-ray radiography the progression of multiple shockwaves through the sample can be recorded and the thermodynamic properties of highly compressed WDM states can be measured. The Nike laser facility also provides more hands on access than other national laser facilities, a key part in educating graduate student and post-doctoral researchers. To address the intellectual challenges of WDM research in a meaningful way also requires interactions with national laboratory scientist who can offer expertise in designing and fielding experiments and analyzing the data.

What is needed to grow academic programs in WDM in the U.S. is a mechanism by which experimental interactions between academic groups and national laboratory scientist can be supported. This requires grants that are lead by an academic principal investigator that can support the mechanism of the experiments (targets, travel, student costs etc.) and the collaborating national laboratory scientist to engage with the academic in a meaningful way.

• Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.

A program that provides funding support for collaboration between academic research programs and scientist at national laboratories in the area of WDM is required to build a vibrant academic WDM research community. Support for these collaborations that is separate from other funded programs is critical because the timescales and objectives of academic research at a university and programmatic research at a national laboratory can be different. These collaborations will educate and train post-docs and graduate students in WDM research and grow the community needed to research new areas of inertial confinement fusion science.
Figure 1: Temperature and density displaying the boundaries between different methods for understanding materials along with Jupiter’s core and pathway for inertial confined fusion$^{16}$. 

\[ 10^{-6} \leq \text{Density (g/cc)} \leq 10^6 \]

\[ 10^{-6} \leq \text{Temperature (eV)} \leq 10^6 \]